Development and Testing of the Regeneratively Cooled Multiple Use Plug Hybrid (for) Nanosats (MUPHyN) Motor

Shannon Eilers,
Graduate Research Assistant

Stephen Whitmore, Associate Professor

Chimaera Propulsion Group
Mechanical and Aerospace Engineering Department
Utah State University

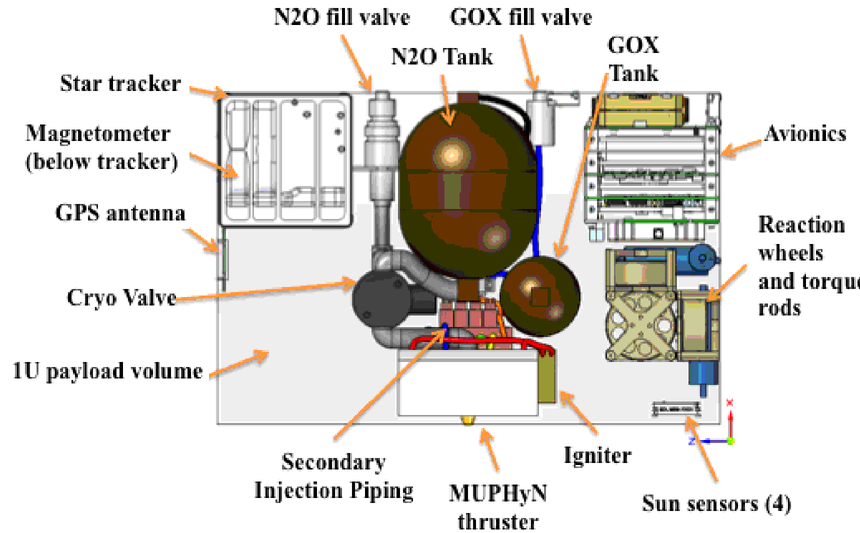
Outline

- MUPHyN Research Motivation and Development Overview
- Aerospike Regenerative Heat Transfer Overview
- MUPHyN Prototype and Experimental Apparatus
- Prototype Test Results

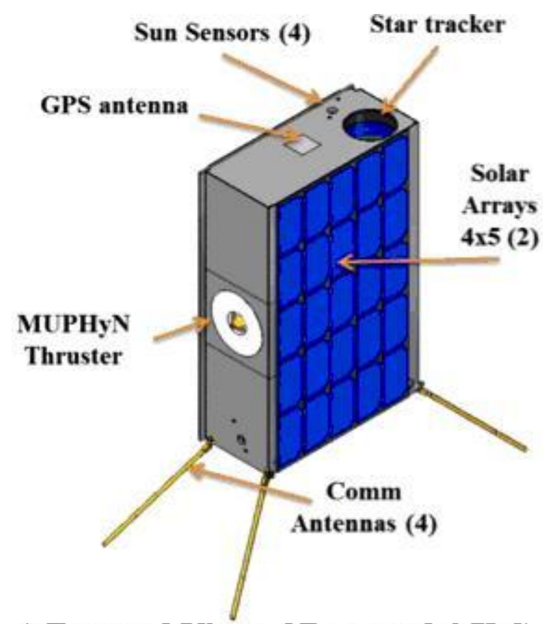
MUPHyN Overview

Research Motivation

- NanoSats (CubeSats) currently do not have propulsive capability
- A wide range of missions open up if satellites have significant maneuvering potential
  - satellite swarms
  - interplanetary missions from GTO
  - targetable reconnaissance
  - extended mission duration
- Challenges:
  - NanoSat propulsion is limited by risks to primary payload
  - Hybrid rocket motors mitigate many of these risks but do not fit well into a small-sat form factor.

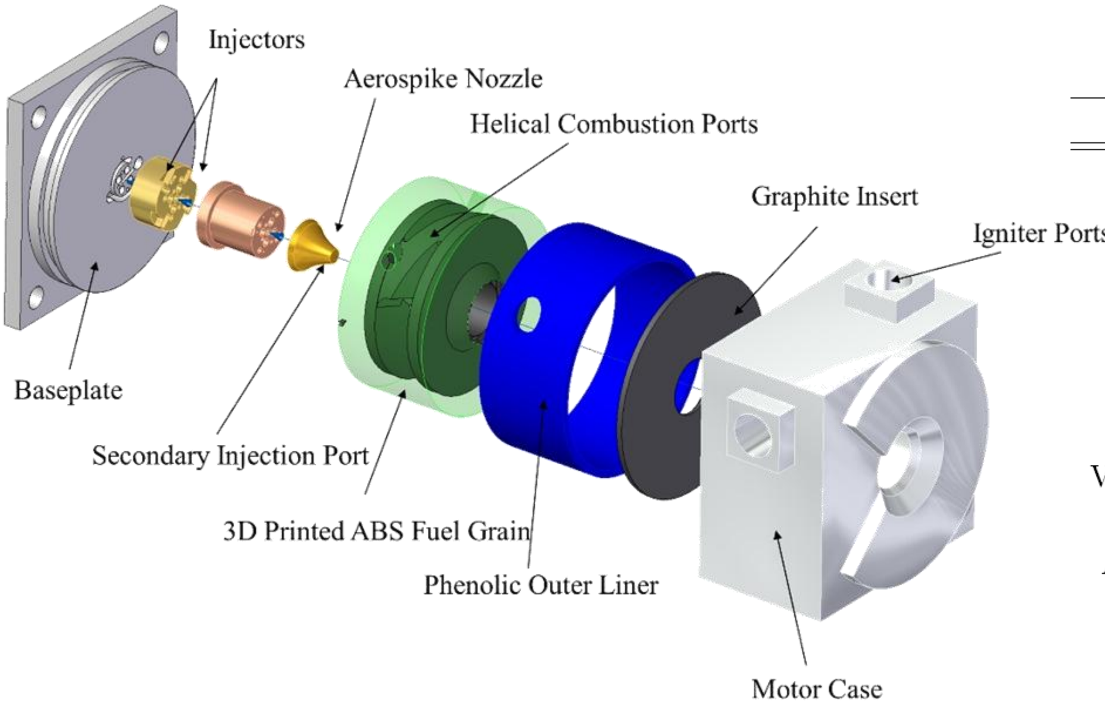


b) Internal Component Layout



a) External View of Proposed 6-U CubeSat

Prototype Overview



Parameter	Value
Outer Throat Radius	1.2 cm
Chamber Pressure	775.6 kPa
Specific Heat Ratio	1.27
Molecular Weight	24.247
Expansion Ratio	2.25
Viscosity	0.844 mP
Chamber Temperature	3046 K
Viscosity Temperature Exponent	1.5
Convergent Surface Length	0.75 cm
Aerospike Surface Temperature	400 K

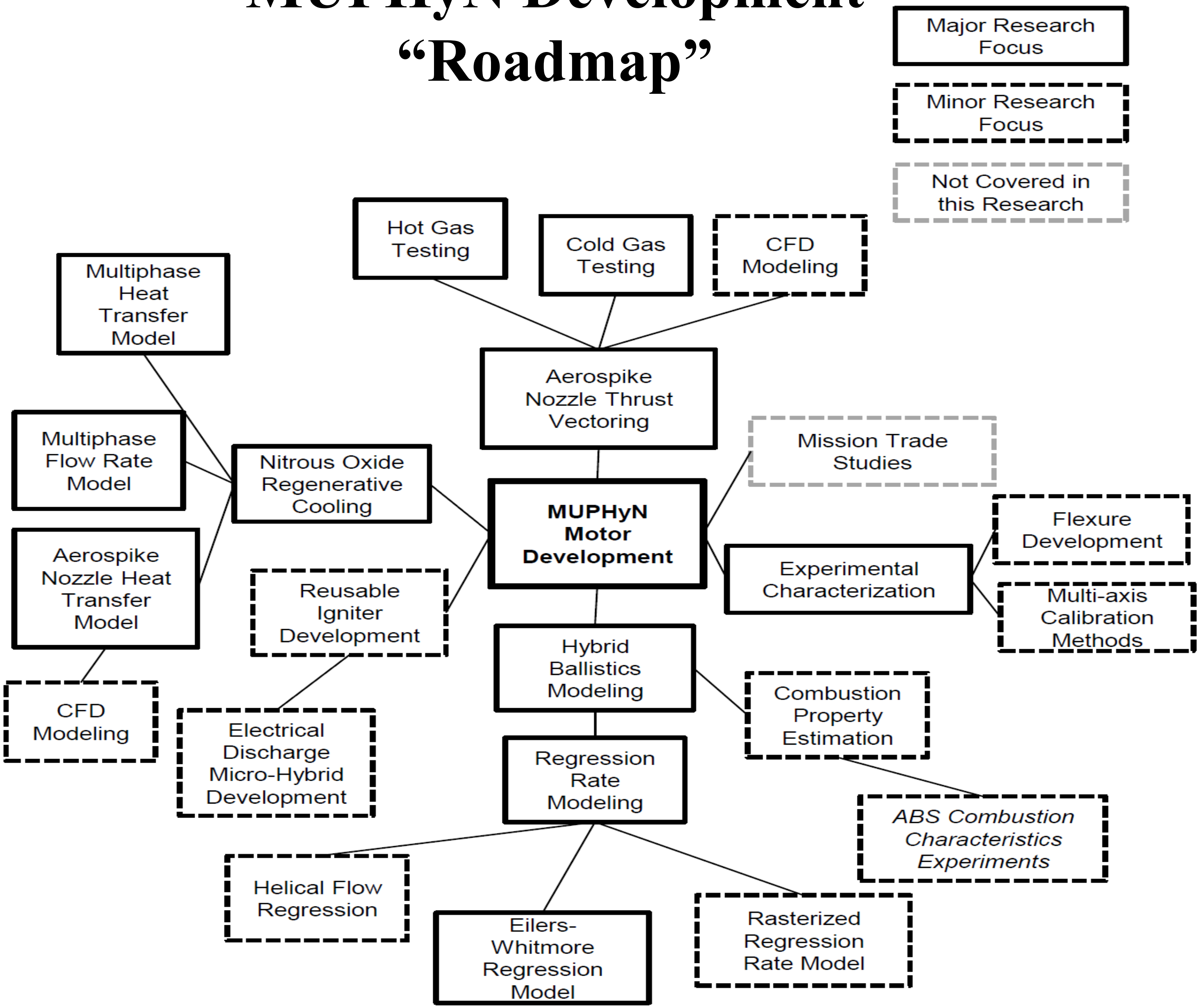
- Prototype Objectives:
  - provide capability for hot gas main flow thrust vectoring tests
  - demonstrate feasibility of regenerative cooling
  - demonstrate feasibility of motor form factor
- Not mission optimized or intended to provide high accuracy heat flux measurements

MUPHyN Development Overview

• MUPHyN Thruster prototype features several design options uniquely suited for nanosat applications

- **Non-toxic, safe N2O and ABS used as system propellants**
  - *-Simplicity of monopropellant hydrazine flow path with enhanced I_{sp}, and smaller form factor*
- **Non-mechanical thrust vectoring using secondary fluid injection on a compact, truncated aerospike nozzle**
  - *-Secondary injection thrust vectoring replaces RCS thrusters, controls attitude during burns*
  - *-Aerospike nozzles allow higher expansion ratios in significantly smaller volume.*
  - *-Regeneratively cooled center plug on aerospike nozzle*
- **A highly compact form factor enabled by digital manufacture of fuel grain segments using Fused Deposition Modeling (FDM).**
  - *-Embedded helical fuel grain port enhances surface mixing and heat transfer to fuel grain*
  - *-Highly enhanced fuel regression rates*
- **Non-pyrotechnic Ignition System**

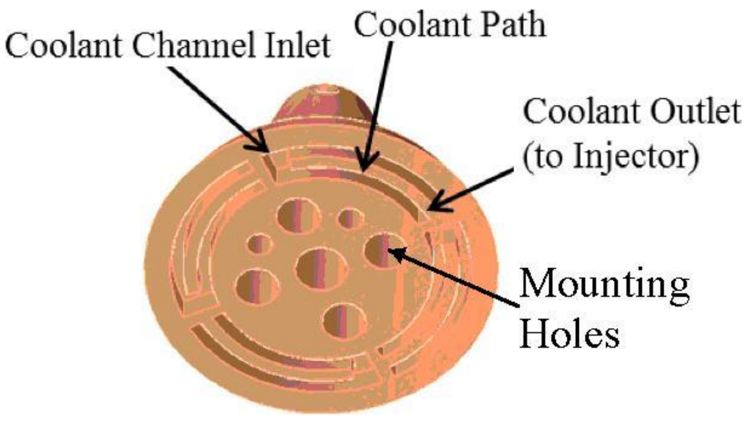
MUPHyN Development "Roadmap"

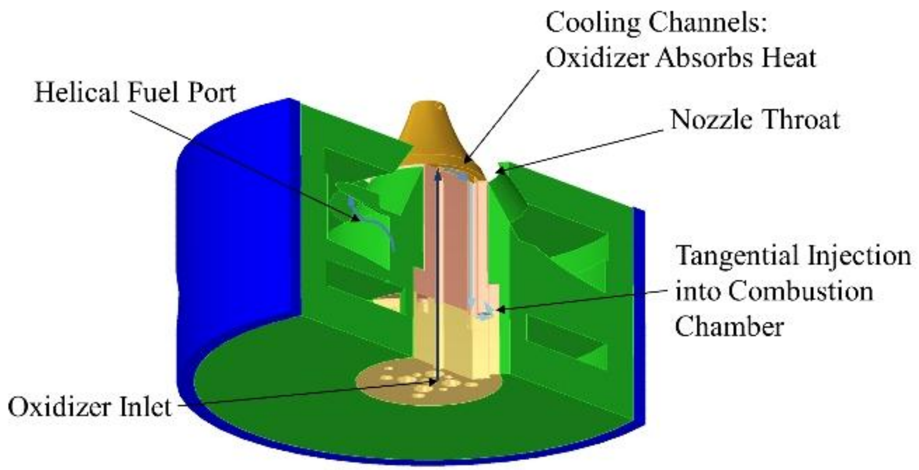


Heat Transfer Analysis

Regenerative Cooling Overview

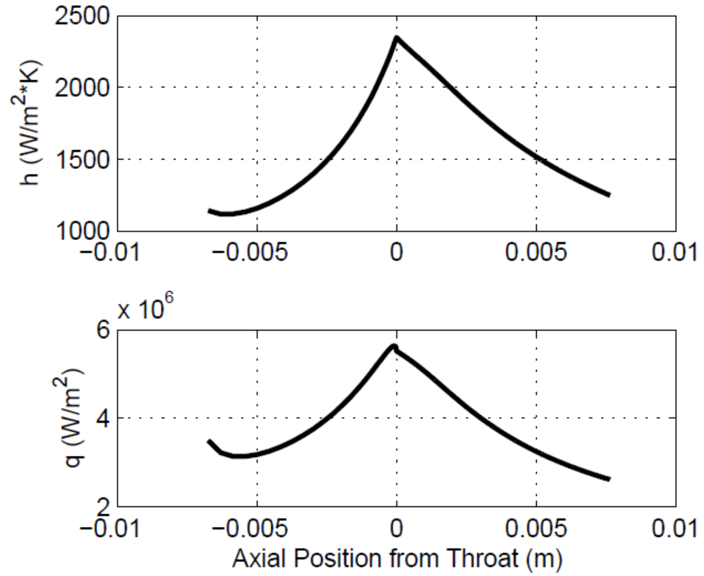
- Aerospike nozzles have higher heat loads than bell or conical nozzles
- Thin throat areas also make ablation much more of a problem.
- At least part of the solution is regenerative cooling.
- Work by Lemieux at Cal Poly demonstrated that nitrous is a workable coolant.

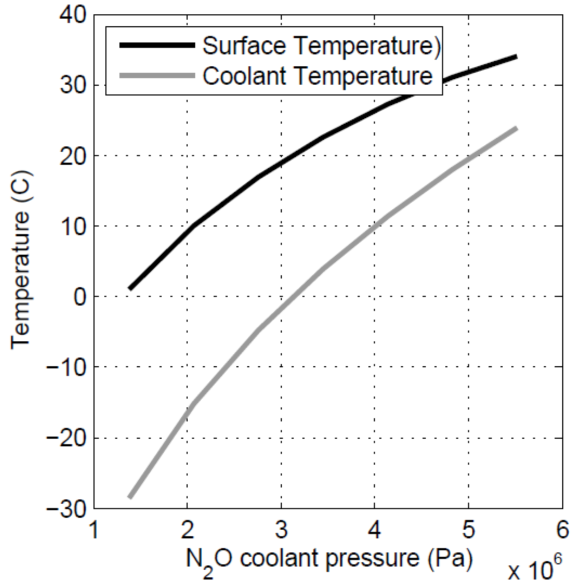




Aerospike Regenerative Cooling

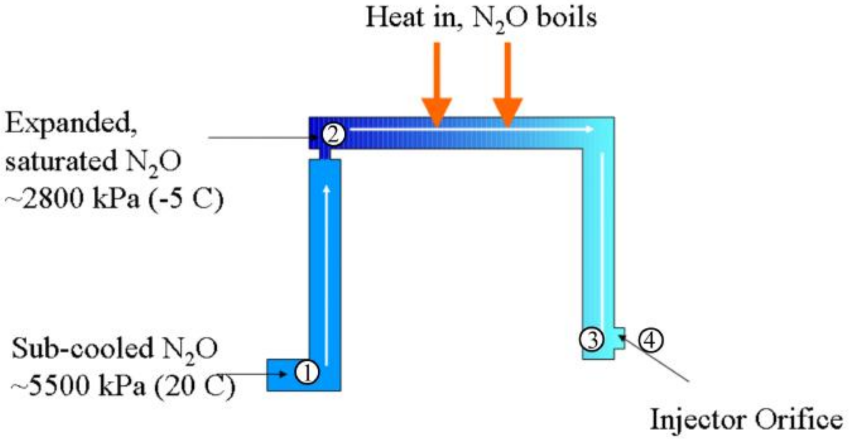
- Aerospike heat loading was calculated from methods by Mayer for annular nozzle configurations
- Total heat loading ~ 3500 Watts
- Coolant side transfer calculated from common multiphase models
- Fluid properties calculated from Helmholtz relations by Span and Wagner.

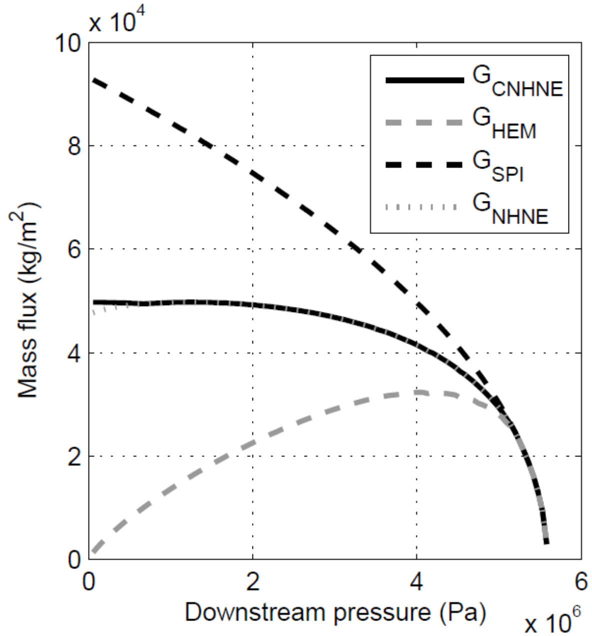


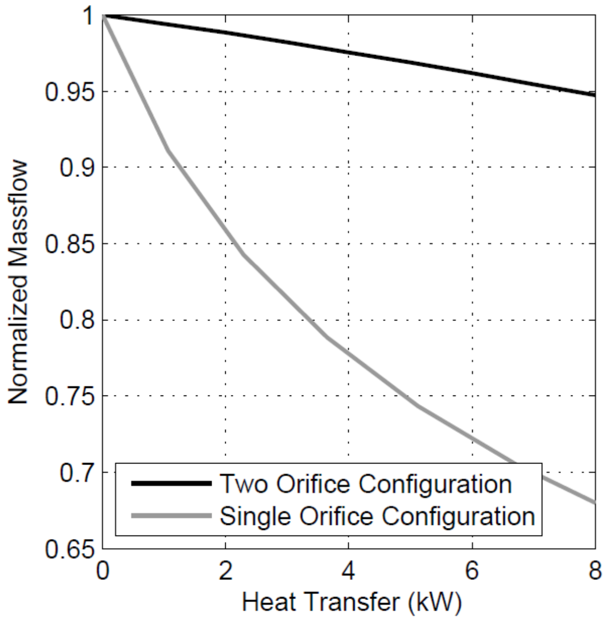


Multiphase Flow Rate Calculation

- Flow rates were calculated via method extended from work by Dyer et. al
  - Modified to numerically "choke" at low downstream pressures
- A "two orifice" configuration was chosen to limit mass flow rate/heat transfer coupling.
  - Somewhat limits cooling capacity



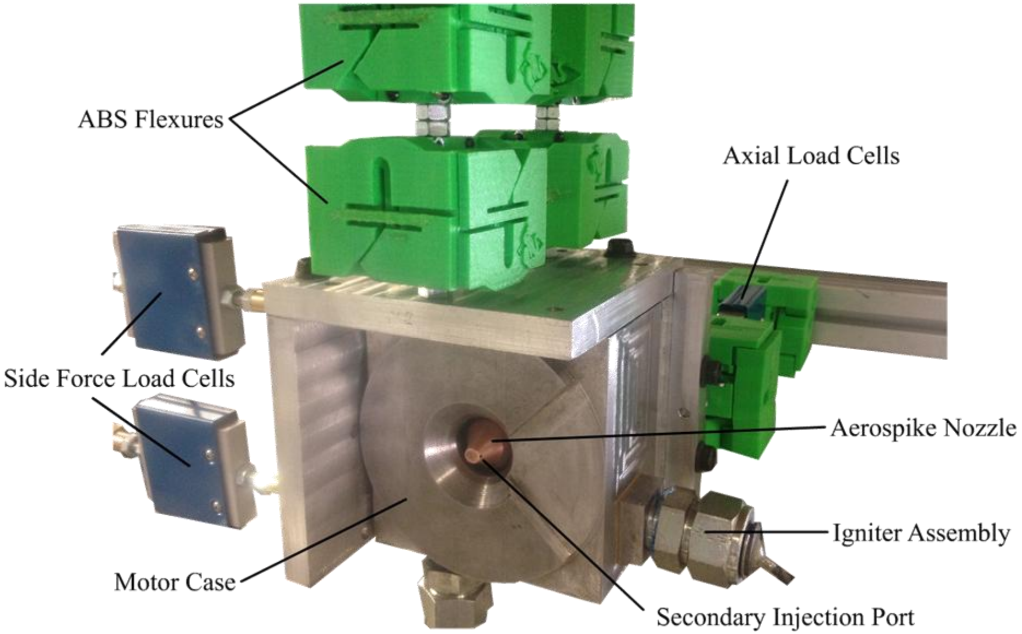




Experimental Apparatus

Test Stand Overview

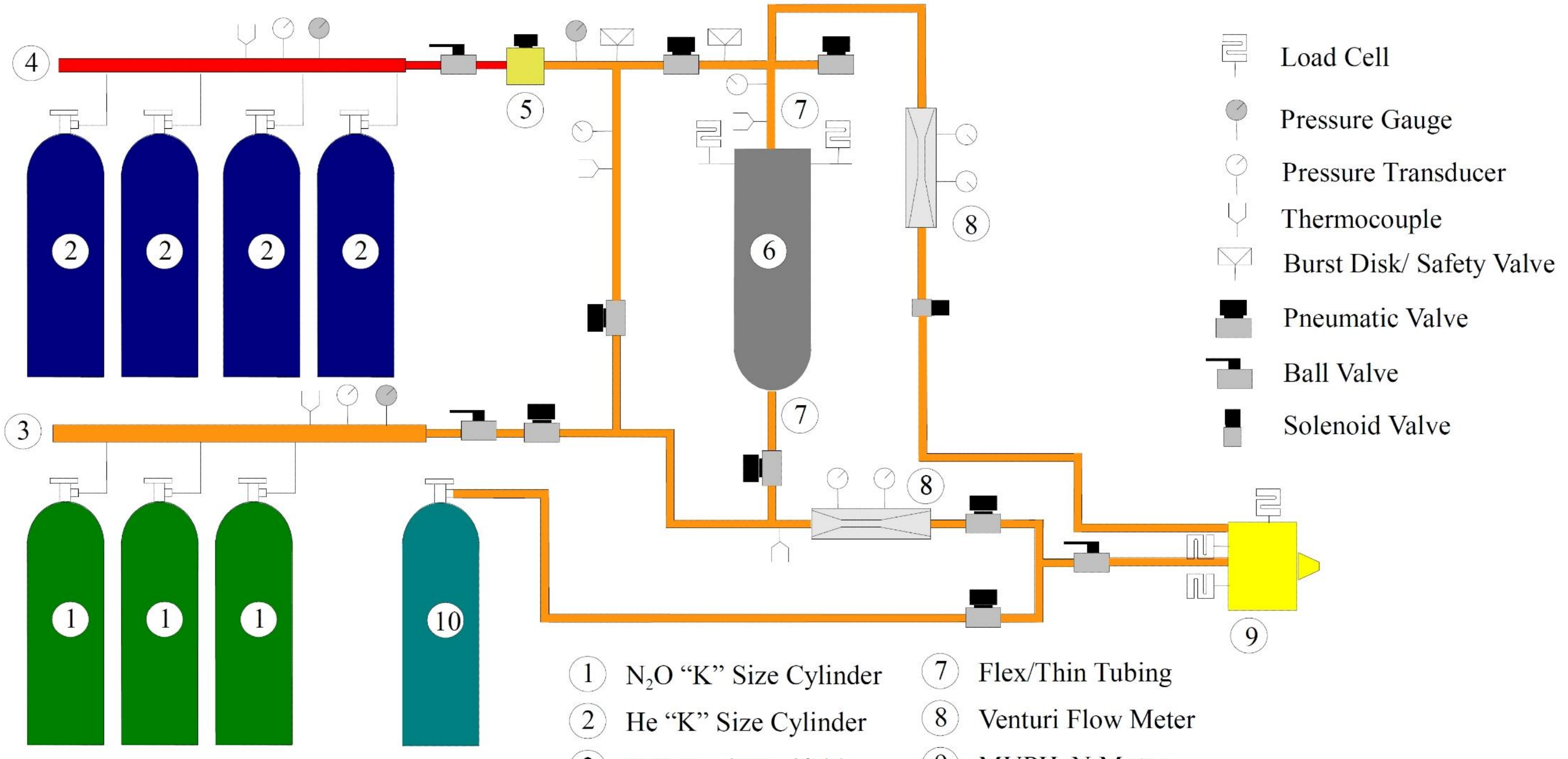
- Motor was tested in a 4 DOF test stand
- Tested in the Jet Engine Test Cell on the USU Campus
- Axial load cells are each 200 N capacity, side load cells each 25 N capacity
- Custom designed fabricated flexures were used in order to measure both thrust and much smaller side forces at same time
  - Printed out of ABS for about $30-$40 each
- Stand was calibrated using a simultaneously multi-axial calibration method
- Mass flow rates measured with custom designed Venturi flow meter



Utah State University

Mechanical & Aerospace Engineering

MoNSTeR Cart Piping and Instrumentation



2200 psi 800 psi 100 psi

1. N_2O "K" Size Cylinder
2. He "K" Size Cylinder
3. N_2O Feed Manifold
4. He Feed Manifold
5. He Regulator
6. Run Tank
7. Flex/Thin Tubing
8. Venturi Flow Meter
9. MUPHyN Motor
10. CO_2 "K" Size Cylinder

MUPHyN Motor Development

Test Results

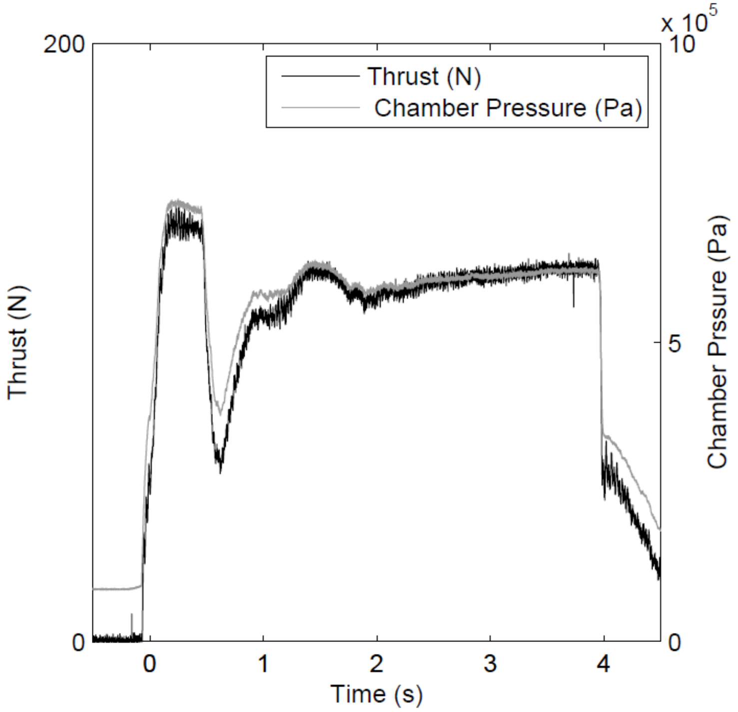
Test Fire Video

- Test Fire HF7
  - Last test to date in series
  - Fuel Grain “Poppyseed”
  - Oxygen secondary injection

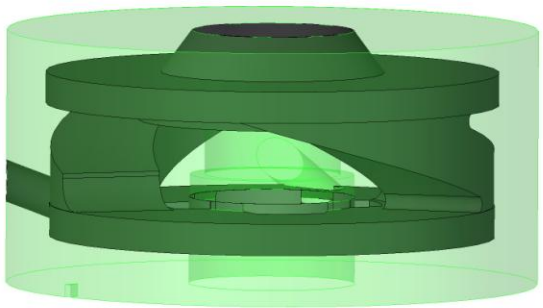
Test Fire Overview

Test No.	Burn Time (s)	Isp (s)	Total Impulse (Ns)	O/F Ratio	Secondary Injectant	Approx. Ox. Flow Rate (kg/s)
HF1	3	137	487	3.16	none	0.088
HF2	3	122	370	4.14	Helium	0.077
HF4	3	128	400	3.13	Helium	0.077
HF5	3	106	320	3.16	Nitrogen	0.072
HF6	4	144	450	3.35	Nitrogen	0.060
HF7	4	142	469	3.38	Oxygen	0.063

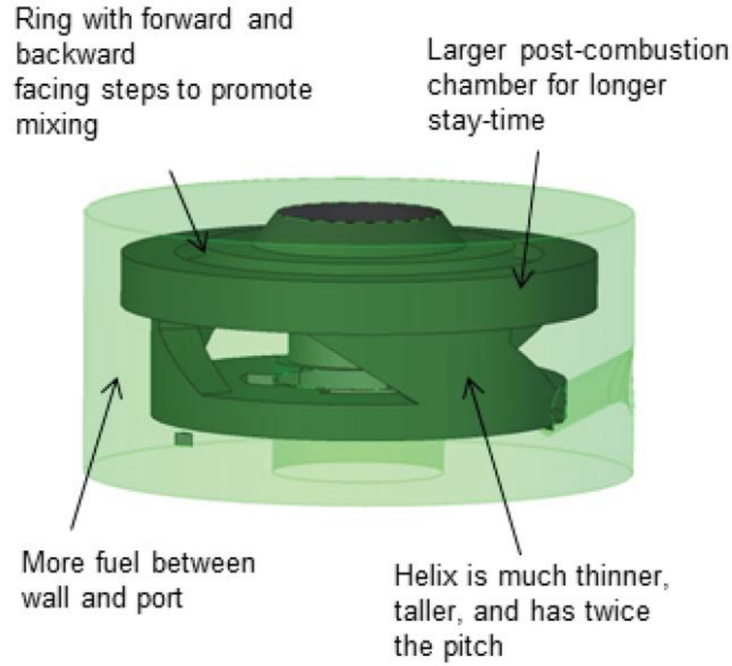
- Tests showed stable combustion
- Specific impulses ranged from 106 s to 144 s, depending on fuel grain configuration
- Tests showed substantially increased regression in helical fuel grains



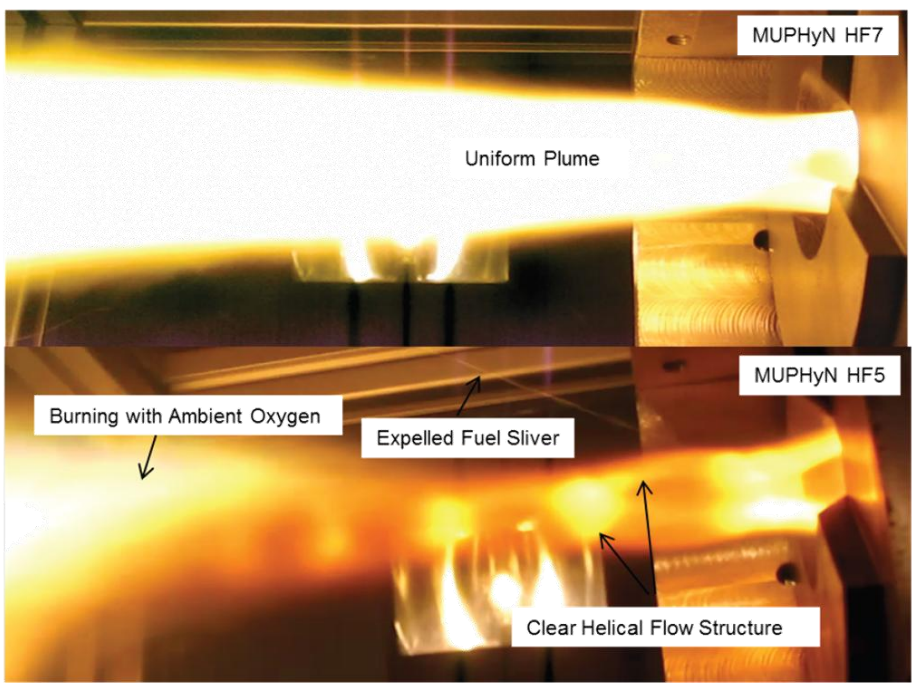
Fuel Grain Geometry



HF5 – “Dark Chocolate”



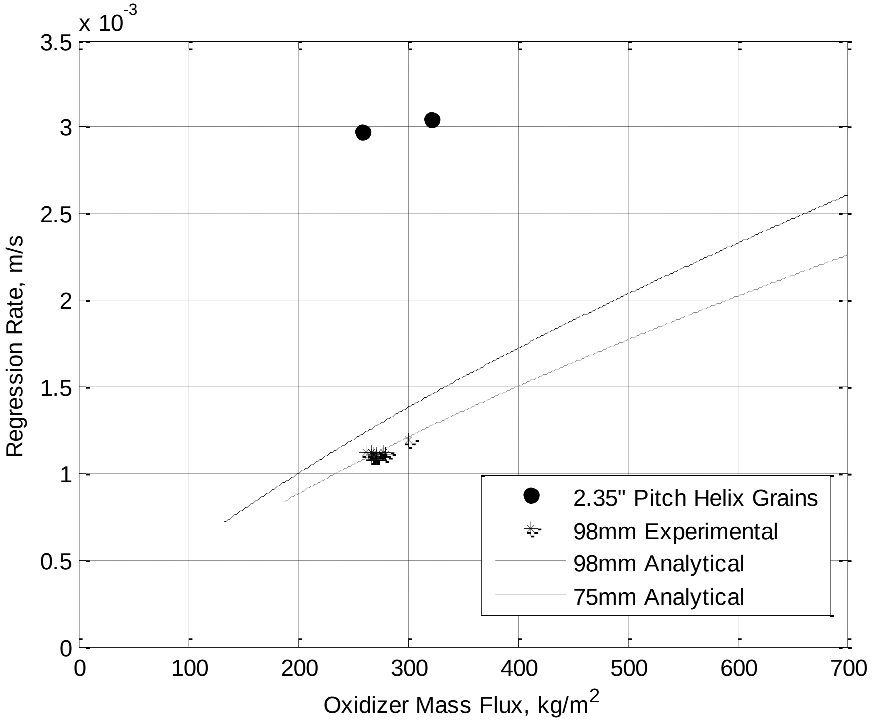
HF7 – “Poppyseed”

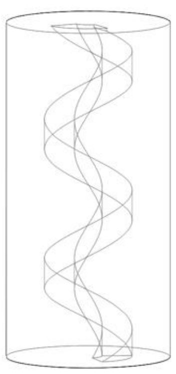


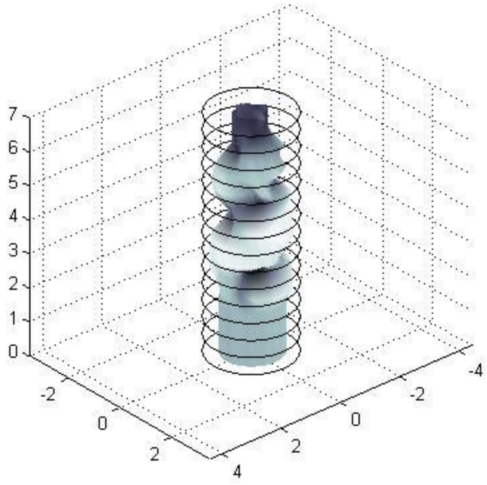
- Combustion efficiency shows strong dependence on fuel grain configuration
  - Change between HF 5 and HF 6 increased Isp about 15%
  - Change was clearly visible from the plume
  - Fuel mass flow rate still to high

Preliminary Helical Port Results

- Helical fuel ports
  - boost surface area
  - increase regression rate
    - Helical friction increases
    - Density variation effects
- Increase mixing
- Regression rate calculated from average surface area
- Mass flux calculated from average “effective diameter”

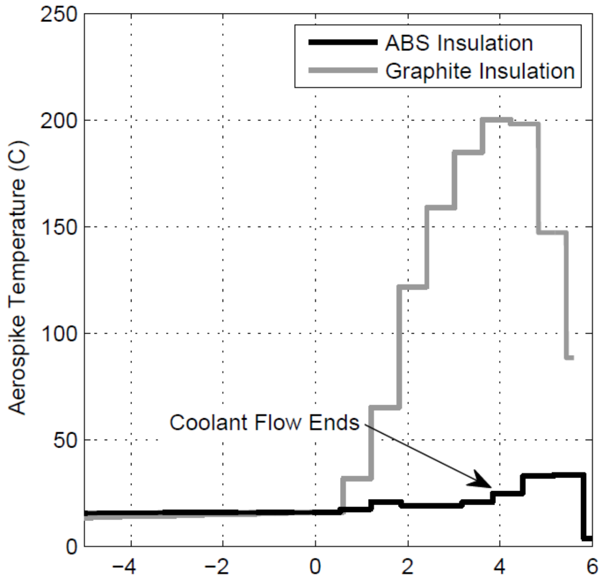


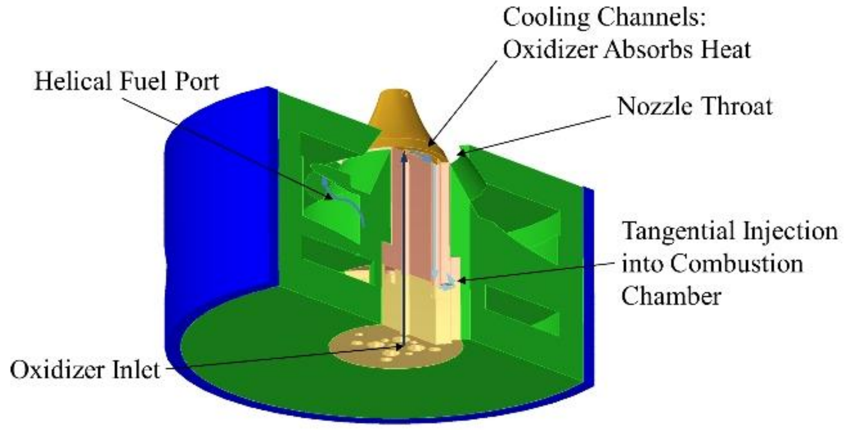




Cooling Test Results

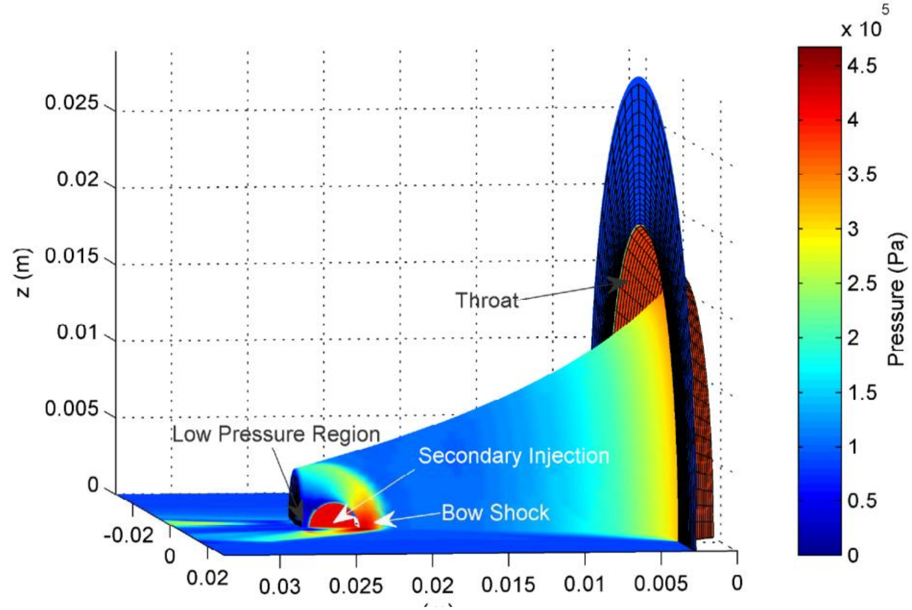
- Aerospike temperature stayed well within material temperature limits
- No motors melted or exploded!
- Spike temperature decreased markedly after graphite insulation around center column was replaced with ABS – printed into fuel grain
- No direct measurement of heat flux was made, but internal temperature agreed well with estimates.

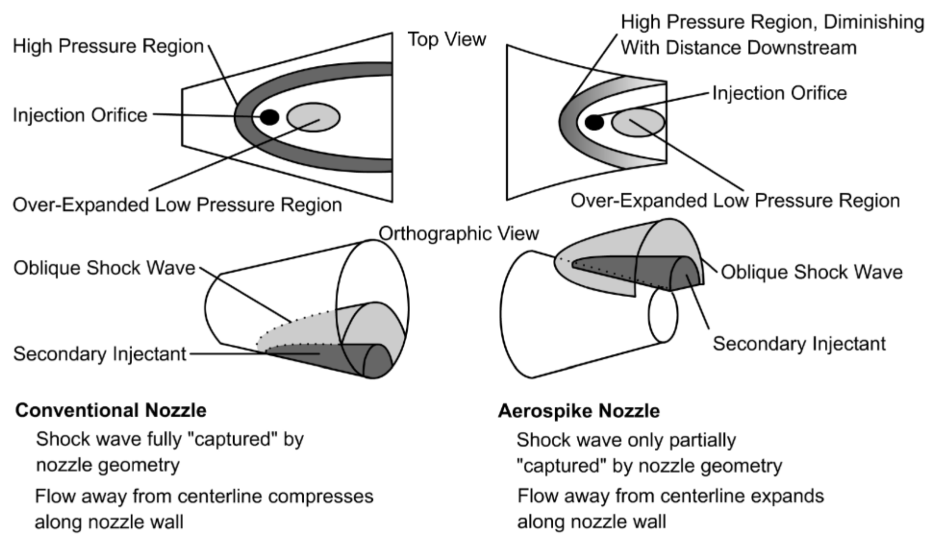




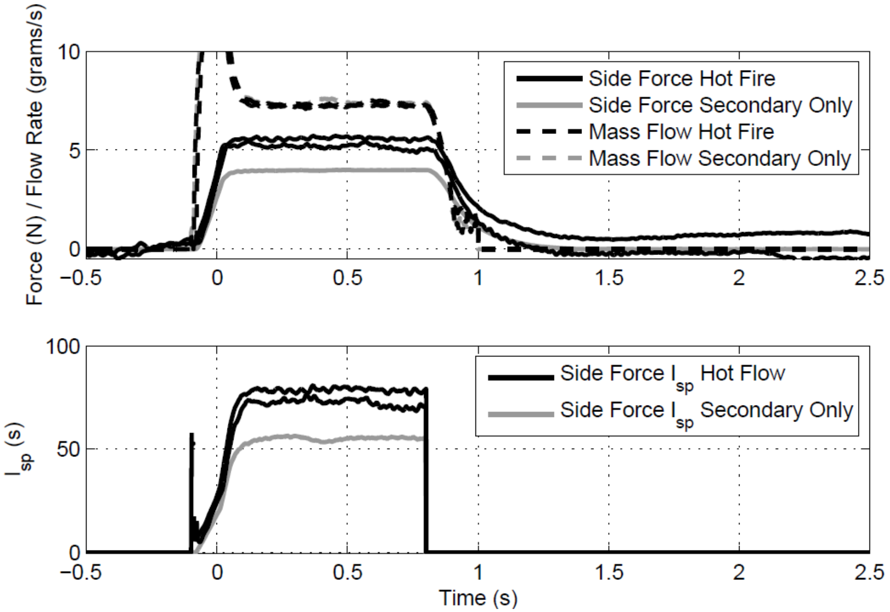
Aerospike Nozzle Thrust Vectoring

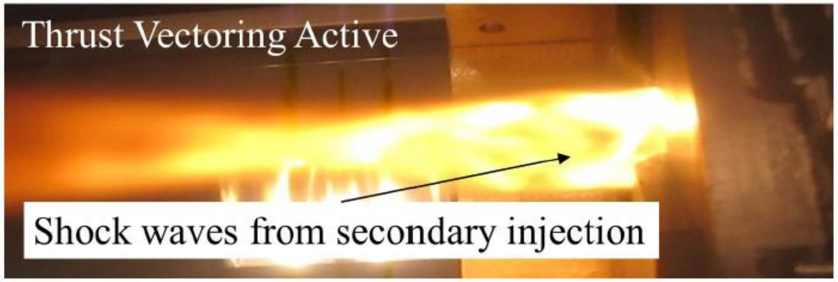
- Aerospike nozzle thrust vectoring has different properties than vectoring in conical or bell nozzles
  - secondary port can be active without main flow on
  - vectoring is more efficient when port is near end of aerospike nozzle
- Cold flow tests on aerospike nozzles in 2011 demonstrated amplification factors of about 1.4 (side force with/without primary flow)





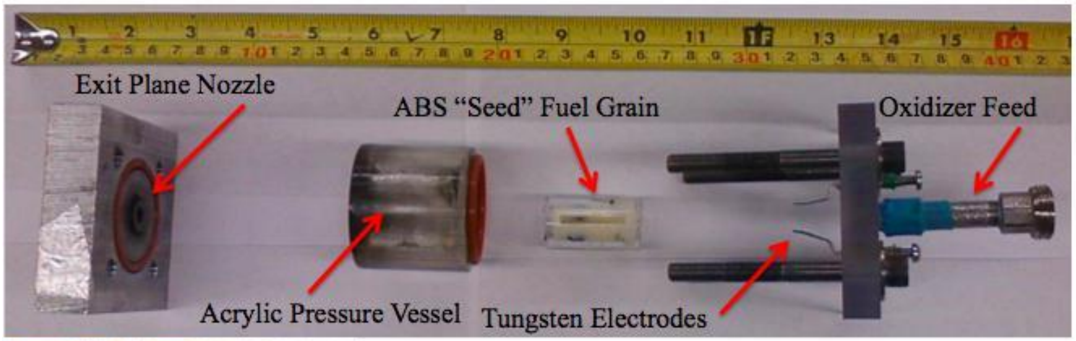
Thrust Vectoring Test Results



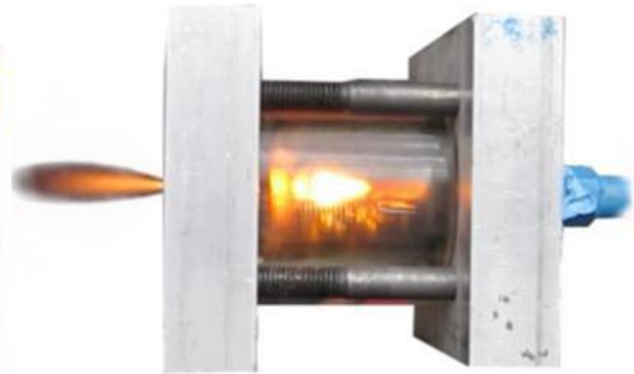


Injectant	Secondary Flow Only Isp (s)	Isp with Primary Flow (s)	Amplification Factor	Thrust Vectoring Angle (deg)	Injectant Static Pressure (MPa)
Nitrogen	51.0	67.1	1.32	1.95	3.5
Helium	121.3	165.5	1.36	3.63	5.7
Oxygen	55.2	73.1	1.32	2.63	3.5

Igniter Development



a) Exploded View



b) Prototype Ignitor Being Test Fired

- Prototype igniter fabricated out of FDM – ABS with conductive fuel layer
- Ignition uses electrical discharge in GOX environment
  - Gox as top pressureant in nitrous system has many advantages
- Up to 27 ignitions have been demonstrated on same igniter fuel grain
- Electrical ignition uses less than 5 Joules per fire… used much less for earlier tests with stun gun.

Questions?